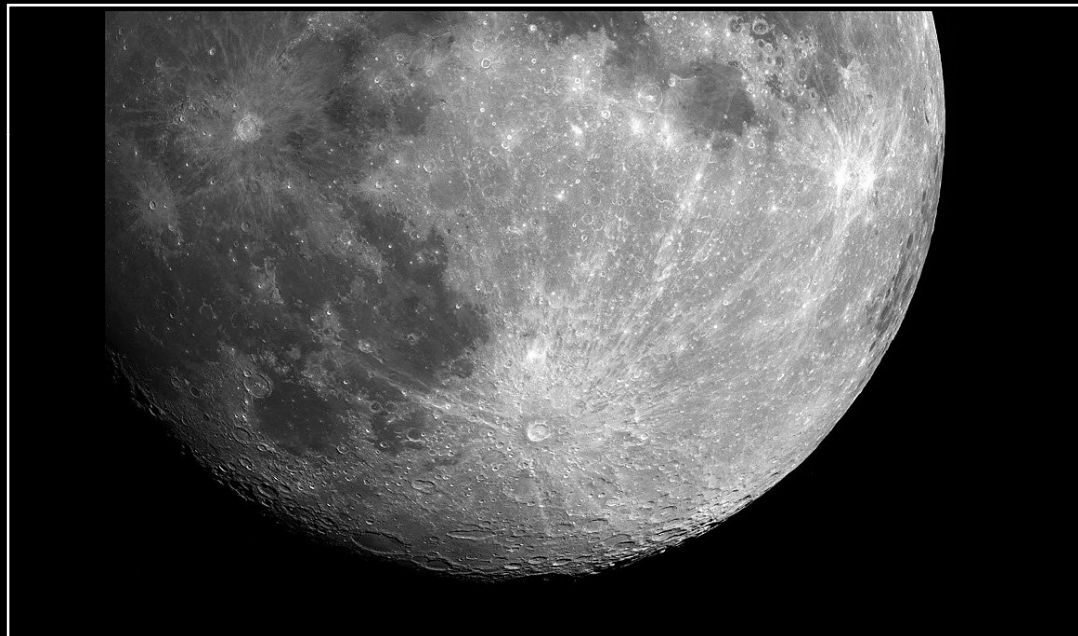


Lunar Site Preparation and Outpost Setup Workshop

October 20 & 21, 2009
Huntsville, AL

Implications of Geology for Construction

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American Society of Civil Engineers
Aerospace Division, Space Engineering & Construction Committee

NASA, Constellation Program
Lunar Surface Systems, Habitation Team, MSFC Advanced Concepts Office

Menu

Basic Geology and Conclusions (Dessert First)

Apollo Vistas and Interpretation (Cheese and Fruit)

Minerals of the Moon with
Comparisons with Engineering Materials (Main)

Particle Composition, including Caveats (Soup)

Thin Sections of the Regolith (Appetizers)

Simplified Summary of Lunar Geology

Data

Initial lunar rock (highlands) ~ norite.

Subsequent basaltic volcanic (& other)flows.

Hypervelocity impacts in a vacuum largely destroyed original rock and produced a lot of glass.

Resulting broken material covering surface = Regolith.

Conclusions

Regolith is NOT soil!

Composition is relatively restricted compared to Earth materials.
It is roughly equivalent to broken igneous rock plus glass.

Particle Size

Data

Net result of continuing meteor bombardment.

Impacts both reduce particle size, shock weld existing particles and melt material.

Surface of Moon is a mixture of fragments -

Size range: nanoscopic to large blocks of rock.

Mixture believed to be meters (kilometers?) deep everywhere.

For Apollo mission samples -

typical average particle sizes from ~ 30 to 100 μm .

Conclusions

The regolith commonly has very fine particle sizes.

Depth to bedrock is an almost meaningless concept.

Sorting

Data

All natural Terrestrial materials made of particles show more or less sorting based on size, shape and composition. This is due to interactions of fluid flow and gravity.

There are no natural fluids on the Moon except for temporary occurrences of molten glass.

Energy added to the lunar surface sufficient to cause particle motion will mix but not sort.

Conclusions

For any reasonable sized sample of the regolith from the top few meters it is possible, and even probable to have particles of all size ranges and with any lunar component in the sample.

Layering which affect mechanical properties does not exist.

Particle Shape and Texture

Data

Particle shapes can be anything from perfect spheres to wildly formed pieces of splatter-welded material.

The average aspect ratio of particles is estimated to be less than 0.5.

Internally, the particles are commonly shattered. The affect on mechanical properties is totally unquantified.

Conclusions

Mechanical modeling of the regolith at the particle level is extremely problematic.

Angular edges of the particles have not been mechanically abraded or smoothed.

General Conclusions

The surface of the Moon is covered in regolith, which is NOT soil!

The regolith is shattered igneous rock plus glass.

The particles are unsorted, unweathered and not abraded.

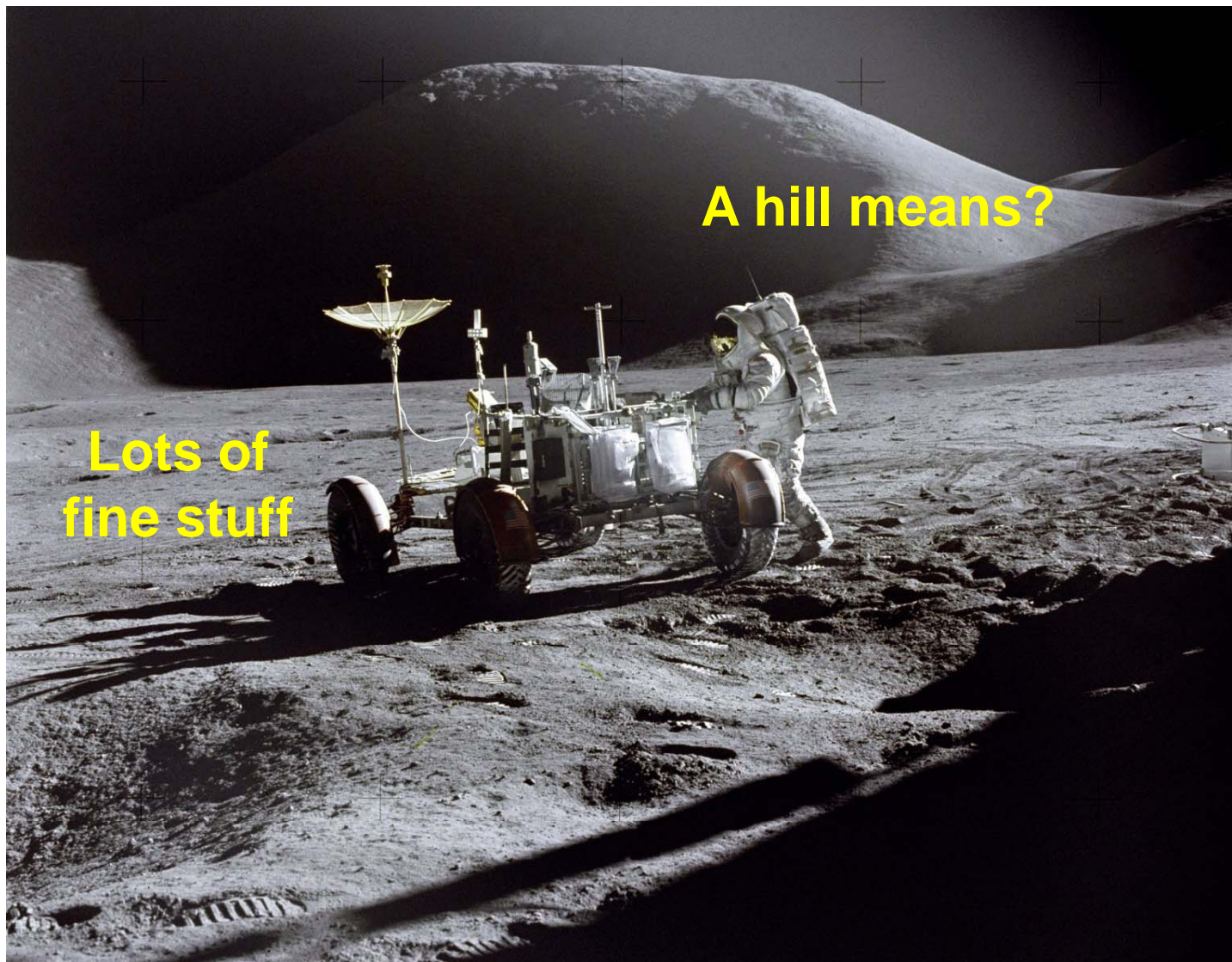
Modeling of the regolith at the level of individual particles will be very problematic.

Modeling of the regolith, if successful for one area, will be successful for most other areas if variation in particle size is addressed.

Apollo Vista 1

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Apollo Vista 2

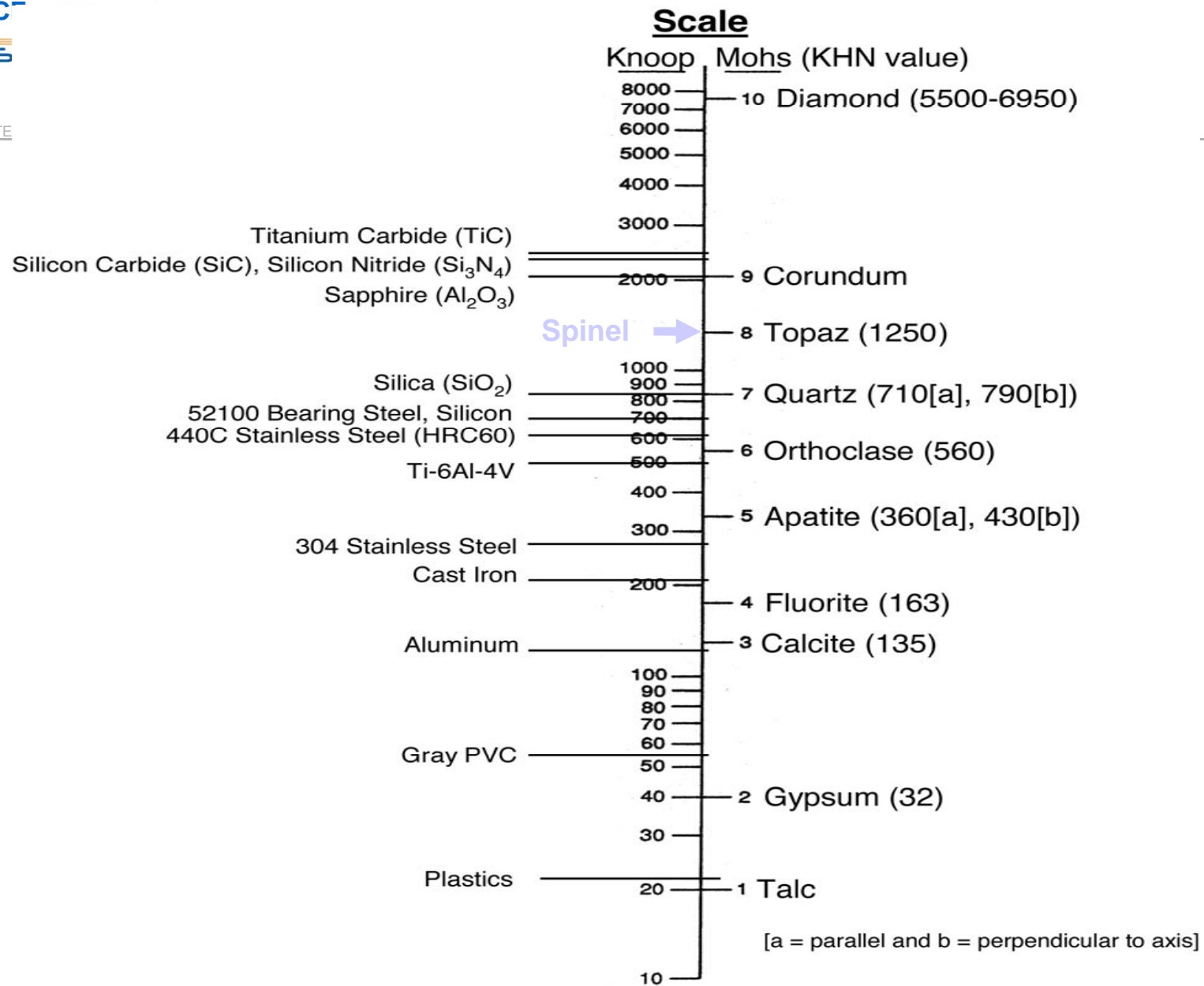
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Major Minerals

Mineral	Mohs	Spec Gravity	Chemical Composition	Abundance
Plagioclase	6.0-6.5	2.73	$(\text{Ca}, \text{Na})(\text{Si}, \text{Al})_4\text{O}_8$	A
Olivine	6.5-7.0	4.39	$(\text{Mg}, \text{Fe})_2\text{SiO}_4$	M
Orthopyroxene	5.0-6.0	3.4	$(\text{Mg}, \text{Fe}, \text{Ca})_2[\text{Si}_2\text{O}_6]$	M
Clinopyroxene	5.0-6.0	3.4	$(\text{Mg}, \text{Fe})_2[\text{Si}_2\text{O}_6]$	M
Spinel	7.5-8.0	3.56	MgAl_2O_4	m - t
Hercynite	7.5-8	3.93	$\text{Fe}^{+2}\text{Al}_2\text{O}_4$	m - t
Ulvospinel	5.5-6.0	4.7	$\text{TiFe}^{+2}_2\text{O}_4$	m - t
Chromite	5.5	4.7	$\text{Fe}^{+2}\text{Cr}_2\text{O}_4$	m - t
Troilite	4	4.75	FeS	t?
Whitlockite	5	3.12	$\text{Ca}_9(\text{Mg}, \text{Fe}^{+2})(\text{PO}_4)_6(\text{PO}_3\text{OH})$	t?
Apatite	5	3.19	$\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl})$	t?
Ilmenite	5.5	4.72	$\text{Fe}^{+2}\text{TiO}_3$	m
Native Iron	4.5	7.87	Fe	t



From Rickman and Street, 2008

Particle Composition

Caveats:

Lunar dust fraction (material $< 20\mu\text{m}$) currently not well characterized.

Some aspects may or may not be important, for example the presence of nanoscopic Fe or vapor deposited rims.

Regolith (macroscopically) is minerals and silicate glass.

A mineral is:

- a naturally occurring substance, with a characteristic, limited chemical composition and a highly ordered atomic structure.

Therefore the range of each mineral's properties is limited AND a mineral's properties are independent of source (lunar or terrestrial).

Optical Scans of Thin Sections

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64002,6019



64001,6031



No sorting. No layering.

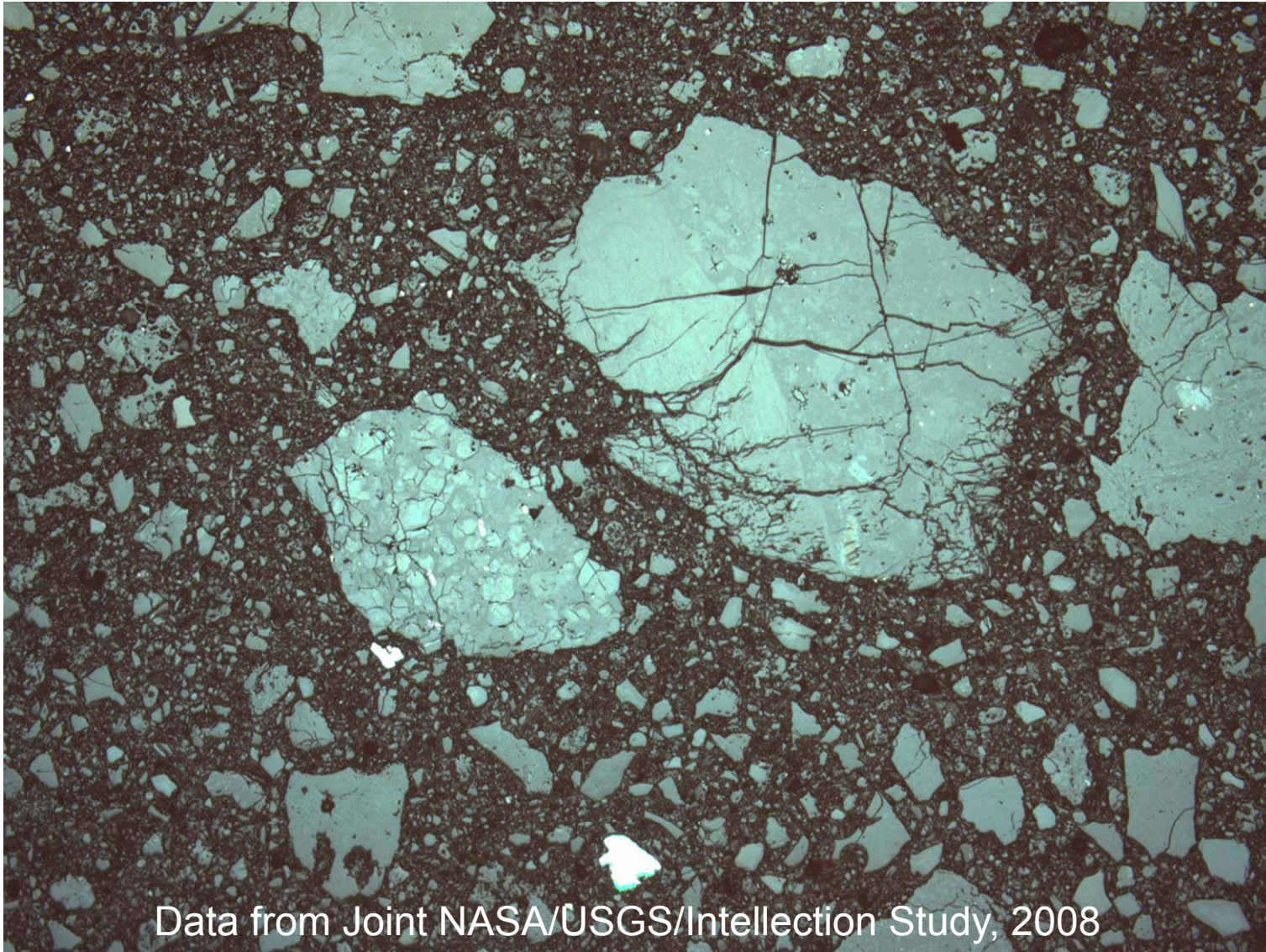
Data from Joint NASA/USGS/Intellection Study, 2008

Particle Shapes and Textures 1

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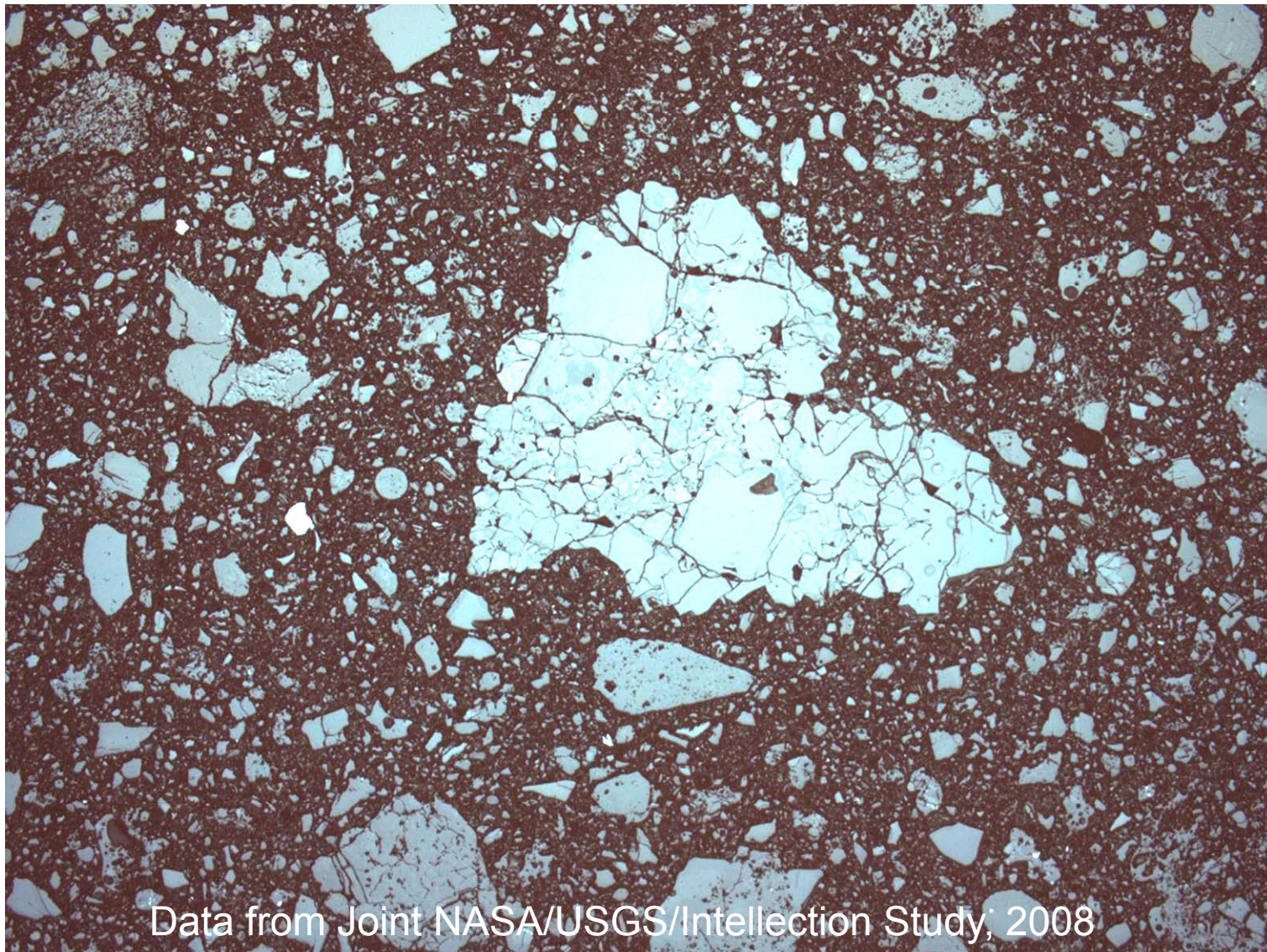
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Particle Shapes and Textures 2

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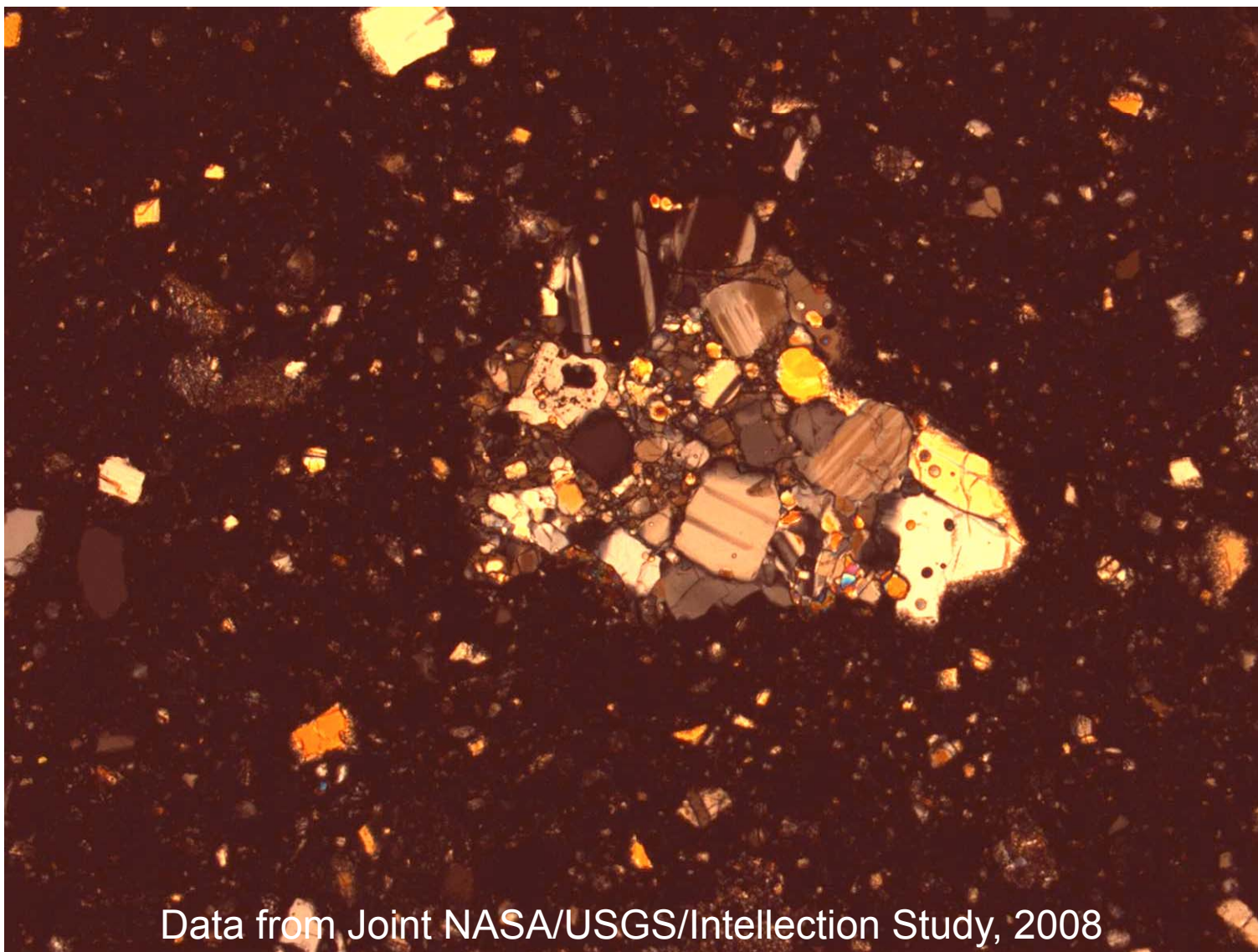
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Data from Joint NASA/USGS/Intellection Study, 2008

Ditto

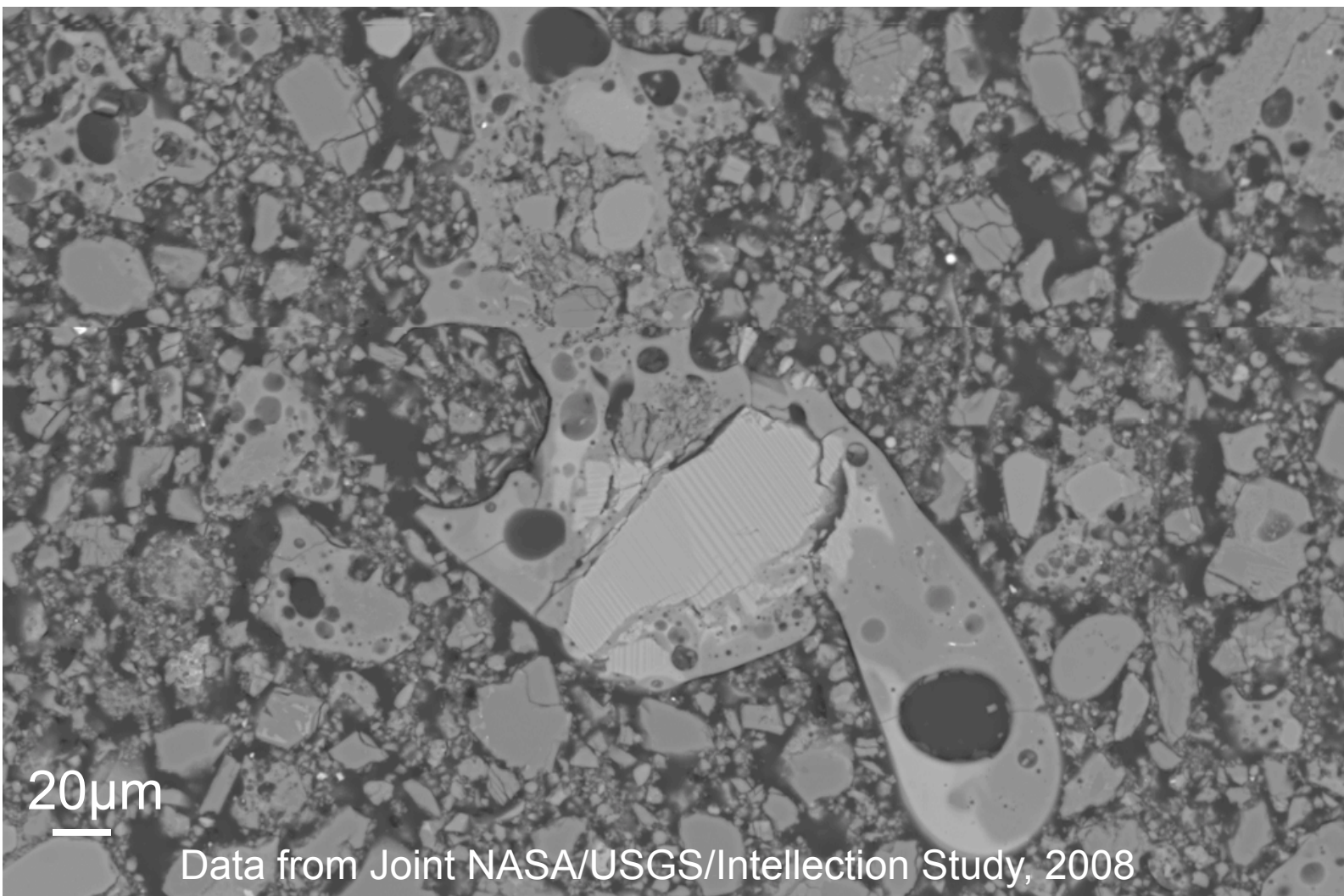
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Data from Joint NASA/USGS/Intellection Study, 2008

Agglutinates

64001,6031



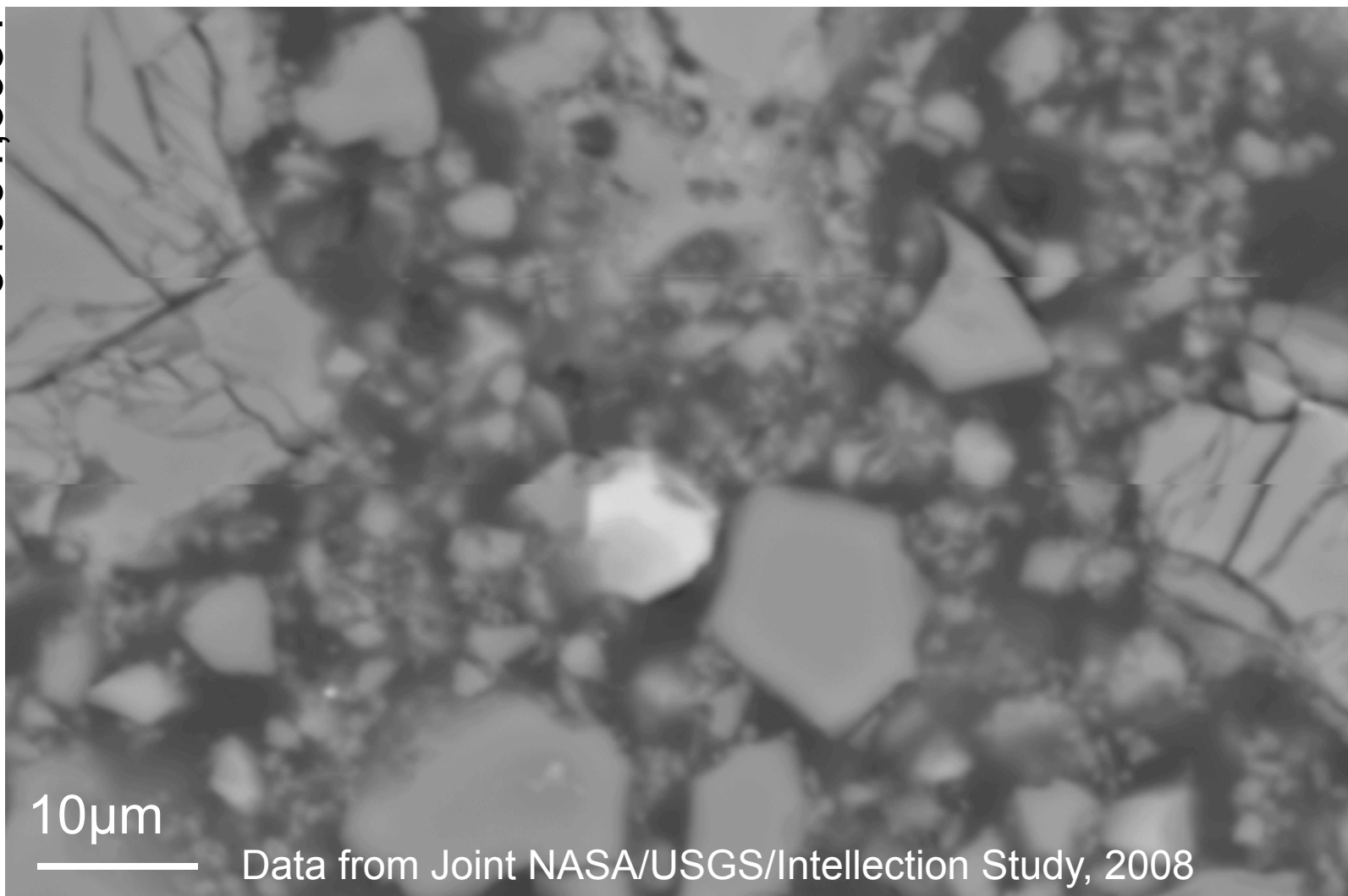
Data from Joint NASA/USGS/Intellection Study, 2008

Scale Invariance

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Data from Joint NASA/USGS/Intellection Study, 2008